Baseband I/Q regeneration Method for Direct Conversion Receiver to nullify effect of I/Q mismatch

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Abstract

Direct Conversion Receiver is the choice of the today's designer for low power compact wireless receiver. DCR is attractive due to low power, small size and highly monolithic integratable structure, but distortions affect its performance. I/Q mismatch is the one of the major distortion which is responsible for performance degradation. In this paper, a novel method for Direct Conversion Receiver is suggested, which makes it insensitive to the I/Q mismatch. Here the classical homodyne architecture is modified to nullify effect of I/Q mismatch. The proposed method can be implemented in the Digital Signal Processing (DSP) back-end section also. This feature makes it acceptable in the already designed/functioning classical homodyne architecture based receiver.

1. Introduction

Direct Conversion Receiver (DCR) offer a low power and very high level of integratable [1] solution for the design of wireless devices. Due to single mixer stage, DCR enables the implementation of the flexibility in the baseband digital signal processing, required by modern wireless communication systems. Other types of receiver architectures require an image filter that can be designed in surface acoustic wave or bulk acoustic wave technology for which the level of the integration is very low [2]. However, the baseband signals I (t) and Q (t) at the output of this receiver can be corrupted by direct current (dc) offset, inphase and quadrature (I/Q) mismatch, local oscillator (LO) leakage, and even order distortion [3-5].

This paper describes the I/Q mismatch problem in DCRs. This distortion is mainly because of two reasons: (i) Local oscillator signal driving the mixers in I and Q branch are not in quadrature phase i.e. 90^0 phase shift, and (ii) Difference in the transfer functions of I and Q branch due to production tolerance, which results in the uneven phase shift to I and Q branch signals. Gain error appears as a non unity scale factor in the amplitude, while phase imbalance corrupt one channel with a fraction of the data pulses in the other channel. Wireless devices for Cognitive Radio (CR) applications are very sensitive to this problem [6]. Therefore, major effort has been put on the removal of this problem nowadays.

Several techniques are proposed in the literature to solve the I/Q mismatch problem. These approaches can be classified in two broad categories: (i) Data - aided approaches and (ii) Blind approaches. Various data-aided techniques are described in [7]-[13]. These approaches are strongly standard dependent because they rely on known pilot or training sequences. As received reference symbols contain the impairments of transmitter and receiver signal processing chain, these methods are suitable for combined mitigation of several impairment sources. [7] and [8] represent compensation of I/Q mismatch with least square approach in combination with frequency offset, while [9],[10] compensate with channel estimation. [11] represents compensation of frequency dependent I/Q mismatch on the transmitter side and [12],[13] both on transmitter and receiver side in MIMO systems.

Various blind methods are described in [14]-[19]. Blind methods rely on statistical properties of the influenced signal. [15] uses the statistical independence between the desired signal and its mirror image for frequency independent I/Q mismatch compensation in low-IF receiver by blind signal separation. In [16] a gradient descent search method in time domain and a frequency domain approach based on a single-tap matrix inversion for frequency dependent I/Q imbalance compensation is presented. [17] provides advanced blind source separation techniques for frequency independent I/Q imbalance compensation in MIMO systems and [18] shows the same for the frequency dependent case by using higher-order statistics in an independent component analysis. The compensation of I/Q mismatch using properness property of the signal is represented in [19].

Data-aided methods give fast convergence and good performance but at the cost of high computational complexity. Blind methods are standard independent and therefore are more flexible in its use, but need longer convergence times and sometimes high implementation effort. As a solution to these problems, an architectural approach has been adopted here to propose a simple solution for I/Q mismatch problem. Here a novel method of I/Q regeneration is proposed with self calibration strategy to nullify I/Q mismatch problem. Self calibration method makes this approach standard independent and simple algorithm makes it fast and computationally less complex. Comprehensive simulated and practically measured results are presented to indicate the effectiveness of the proposed architecture.

2. Analysis of classical DCR

The purpose of an RF direct conversion receiver is to demodulate a signal $a_{RF}(t)$ with carrier frequency f_{RF}, complex envelope $env(t) = I(t) + jQ(t)$, and amplitude A_{RF} using a signal $a_{LO}(t)$ generated by a local oscillator with frequency $f_{LO} = f_{RF}$ and amplitude A_{LO}. The two signals can be represented by the two complex waves.

$$a_{RF}(t) = A_{RF}(I(t) + jQ(t))exp(j2\pi f_{RF}t) \quad (1)$$
$$a_{LO}(t) = A_{LO}\, exp(j2\pi f_{LO}t). \quad (2)$$

The voltages $v_{RF}(t)$ and $v_{LO}(t)$ are obtained by taking the real part of Equation (1) and (2).

$$v_{RF}(t) = A_{RF}(I(t)cos(2\pi f_{RF}t) - Q(t)sin(2\pi f_{RF}t)) \quad (3)$$
$$v_{LO}(t) = A_{LO}\, cos(2\pi f_{LO}t). \quad (4)$$

I(t) and Q(t) represent the inphase and quadrature (I/Q) signals. Figure 1 represents the classical direct conversion receiver using quadrature down conversion, which performs the demodulation of $v_{RF}(t)$.

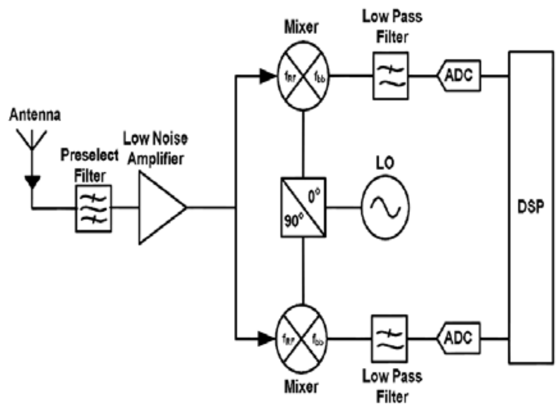

Figure 1: Classical Direct Conversion Receiver

As per Fig.1, RF signal input to mixer-1 and mixer-2 is $v_{RF}(t)$. While, local oscillator (LO) signal to mixer-1 is $v_{LO1}(t) = v_{LO}(t)$ and to mixer-2 is

$$v_{LO2}(t) = A_{LO}\, cos(2\pi f_{LO}t + \pi/2). \quad (5)$$

Output of low pass filter-1 is $v_1(t)$ and of low pass filter-2 is $v_2(t)$,

$$v_1(t) = (A_{RF}A_{LO}/2).I(t) \quad (6)$$
$$v_2(t) = (A_{RF}A_{LO}/2).Q(t) \quad (7)$$

Analog to digital converter (ADC) converts $v_1(t)$ and $v_2(t)$ in digital domain and then applied to back-end digital signal processing (DSP) section to extract the transmitted data bits. Extracting the I(t) and Q(t) signal without distortion is the critical function of the receiver. I/Q mismatch greatly affect the faithful reproduction of I(t) and Q(t) signal at receiver [3]. Next section, describes the proposed method of I/Q regeneration, which nullify the effect of I/Q mismatch.

3. Analysis of proposed method

Here, we introduce I/Q mismatch distortion and then demonstrate the ability of proposed method to nullify effect of distortion on the output of the receiver. I/Q mismatch is introduced by taking different gain and phase for the local oscillator path-1 and path-2. In this case the local oscillator signal to mixer-1 and mixer-2 are

$$v_{LO1}(t) = A_{LO1}\, cos(2\pi f_{LO}t + \phi) \quad (8)$$
$$v_{LO2}(t) = A_{LO2}\, cos(2\pi f_{LO}t + \pi/2 + \varepsilon) \quad (9)$$

where ϕ is the phase shift between transmitted carrier signal and locally generated carrier signal, while ε is phase shift introduced due to non- similarity in design and other factors. Therefore, the output of low pass filters in the presence of I/Q mismatch are

$$v_1(t) = A_1.cos(\phi).I(t) + A_1.sin(\phi).Q(t) \quad (10)$$
$$v_2(t) = A_2.cos(\varepsilon).I(t) + A_2.sin(\varepsilon).Q(t) \quad (11)$$

A system can be written using (10) and (11)

$$\begin{bmatrix} v_1(t) \\ v_2(t) \end{bmatrix} = B \begin{bmatrix} I(t) \\ Q(t) \end{bmatrix} \quad (12)$$

with

$$B = \begin{bmatrix} A_1 \cos(\phi) & A_1 \sin(\phi) \\ A_2 \cos(\varepsilon) & A_2 \sin(\varepsilon) \end{bmatrix}$$

If we suppose that the matrix B is nonsingular, then we obtain

$$\begin{bmatrix} I(t) \\ Q(t) \end{bmatrix} = B^{-1} \begin{bmatrix} v_1(t) \\ v_2(t) \end{bmatrix} \quad (13)$$

With

$$B^{-1} = \begin{bmatrix} \alpha_1 & \alpha_2 \\ \beta_1 & \beta_2 \end{bmatrix}$$

With (13) and the expression of the inverse of matrix B, the expressions of the I(t) and Q(t) signals are

$$I(t) = \alpha_1(v_1(t)) + \alpha_2(v_2(t)) \quad (14)$$
$$Q(t) = \beta_1(v_1(t)) + \beta_2(v_2(t)) \quad (15)$$

Equations (14) and (15) define the relation between I(t) and Q(t) signals, the two output voltages $v_1(t)$, $v_2(t)$ and the four real calibration constants (α_1, α_2, β_1, β_2).

The calibration of the proposed method gives four real constants, which allow faithful I/Q regeneration from the two output voltages in the presence of I/Q mismatch. The four calibration constants can be calculated in two steps as follows.

1) An RF signal with known I(t) , Q(t) sequence (length of N symbols) is injected at input of the direct conversion receiver. This input generates two output voltages that can be used to write

$$C.\begin{bmatrix}\alpha_1\\ \alpha_2\end{bmatrix}=\begin{bmatrix}I(1)\\ \vdots\\ I(N)\end{bmatrix} \qquad (16)$$

$$C.\begin{bmatrix}\beta_1\\ \beta_2\end{bmatrix}=\begin{bmatrix}Q(1)\\ \vdots\\ Q(N)\end{bmatrix} \qquad (17)$$

with $C=\begin{bmatrix}v_1(1) & v_2(1)\\ \vdots & \vdots\\ v_1(N) & v_2(N)\end{bmatrix}$

2) Using the deterministic least-square method, the four constants are calculated as

$$\begin{bmatrix}\alpha_1\\ \alpha_2\end{bmatrix}=(C^T.C)^{-1}.C^T.\begin{bmatrix}I(1)\\ \vdots\\ I(N)\end{bmatrix} \qquad (18)$$

$$\begin{bmatrix}\alpha_1\\ \alpha_2\end{bmatrix}=(C^T.C)^{-1}.C^T.\begin{bmatrix}I(1)\\ \vdots\\ I(N)\end{bmatrix} \qquad (19)$$

After determining these four real coefficients, I/Q demodulation can take place using the two output voltages. There are two methods to perform the calibration of the proposed system.

1) Method of precalibration: The proposed method can be calibrated during manufacture. A known I Q sequence is injected at the RF port for all the frequencies to be used and the coefficients of the calibration are recorded in memory.

2) Method of self-calibration: Here a self calibration method is presented with the proposed method in Figure 2. Advantage of this method is that it is standard independent and activate during the power on of the device or during the ideal/ standby time duration. For explanation purpose the multiplier and adder blocks are represented separately, but usually they are part of the DSP back-end.

When transceiver entered in the self calibration mode, switch S1 becomes open and switch S2 connected to terminal b. Thus antenna section is bypassed. DSP back-end section generates I (t) and Q (t) sequences and applied to Transmitter section. Transmitter section modulates the I (t) and Q(t) sequences and frequency up convert the signal to RF carrier frequency. This RF signal will be applied to receiver section. Receiver section down converts the received signal, low pass filtered the signal and then applied it to multiplier and adder block to regenerate I(t) and Q(t), and at the same time applied to calibration algorithm to calculate calibration coefficients αi, βi.

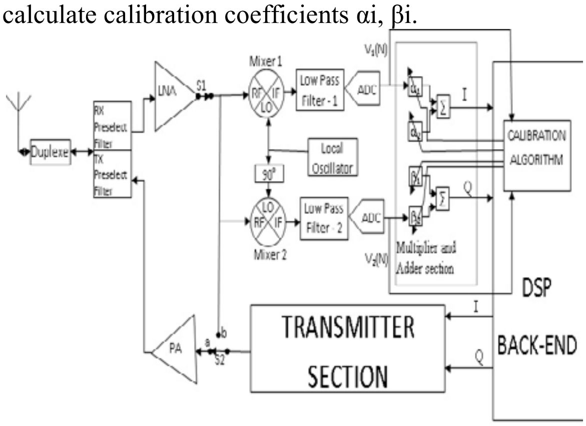

Figure 2: Self-Calibration Method

3.1. Properties of calibration constants

Analysis of properties of calibration constants is required to understand the process of I (t), Q (t) regeneration precisely. Define the five following vectors.

$$\vec{V}_o=\begin{bmatrix}v_{o1}(t)\\ v_{o2}(t)\end{bmatrix} \qquad (20)$$

$$\vec{G}_{\cos}=\begin{bmatrix}A_1.\cos(\phi)\\ A_2.\cos(\varepsilon)\end{bmatrix},\ \vec{G}_{\sin}=\begin{bmatrix}A_1.\sin(\phi)\\ A_2.\sin(\varepsilon)\end{bmatrix} \qquad (21)$$

$$\vec{\alpha}=\begin{bmatrix}\alpha_1\\ \alpha_2\end{bmatrix},\ \vec{\beta}=\begin{bmatrix}\beta_1\\ \beta_2\end{bmatrix} \qquad (22)$$

The system defined by (10) and (11) becomes the vectorial relation

$$\vec{V}_o=I(t)\vec{G}_{\cos}+Q(t)\vec{G}_{\sin} \qquad (23)$$

Equation (14) and (15) can be seen as two scalar products. Using relation (23) and the two vectors defined by (22), we obtain

$$I(t)=\vec{\alpha}\bullet\vec{V}_o=\begin{bmatrix}\alpha_1\\ \alpha_2\end{bmatrix}\bullet\begin{bmatrix}v_{o1}(t)\\ v_{o2}(t)\end{bmatrix} = \sum_{i=1}^{2}\alpha_i v_{oi}(t) \qquad (24)$$

$$Q(t) = \vec{\beta} \bullet \vec{V}_o = \begin{bmatrix} \beta_1 \\ \beta_2 \end{bmatrix} \bullet \begin{bmatrix} v_{o1}(t) \\ v_{o2}(t) \end{bmatrix} = \sum_{i=1}^{2} \beta_i v_{oi}(t). \quad (25)$$

By using the expression of the vector V_o defined by (20) and replacing it in (24), we can deduce the following relation for the I channel:

$$I(t) = I(t)\vec{\alpha} \bullet \vec{G}_{\cos} + Q(t)\vec{\alpha} \bullet \vec{G}_{\sin} \quad (26)$$

By identification, we can write the following relations for the I channel:

$$\vec{\alpha} \bullet \vec{G}_{\sin} = 0 \quad (27)$$

$$\vec{\alpha} \bullet \vec{G}_{\cos} = 1. \quad (28)$$

In the same way, for the Q channel we obtain

$$\vec{\beta} \bullet \vec{G}_{\cos} = 0 \quad (29)$$

$$\vec{\beta} \bullet \vec{G}_{\sin} = 1. \quad (30)$$

Equations (27)-(30) show that the calibration procedure allows the following:
1) Separation between the I(t) and Q(t) signals [with (27) and (29)]: The geometric property is that the vectors α and β are, respectively, perpendicular to the vectors $G_{\sin}$ and $G_{\cos}$.
2) Normalization of vector α and β [with (28) and (30)]: This property allows the normalization of I(t) and Q (t) signals by compensating the amplitude A_i of the received signal, i.e. if A_i is low, the norms of vector α and β are high and vice versa.

4. Results

This section presents the simulation results as well practically measured results. The simulation results are presented in Figure 3 - 5. MATLAB is utilized for the simulation purpose. Fig. 3 presents the effect of phase error between I(t) and Q(t) on the BER. Here the performance of classical DCR and proposed method are tested in the presence of phase error. Classical DCR architecture can maintain its performance during low value of phase error i.e. upto 3^{o}-4^{o} degree. While proposed method can maintain its performance upto sufficient large amount of phase-shift. This indicates that the proposed method is insensitive to the phase shift error. Simulated constellation diagram for the classical DCR and proposed method is presented in Figure 4 and 5. Constellation diagrams also demonstrate that the proposed method is insensitive to the I/Q mismatch.

The test-bench utilized for experimental measurement is shown in Figure 6. Here an RF signal at 2.4GHz with QPSK modulation is provided. Out of the entire data sequence, first sixteen symbols will be utilized for training purpose (i.e. utilized for computation of constants α_i and β_i). Remaining data symbols will be utilized for calculation of BER. The symbol rate utilized is 5 Msamples/s.

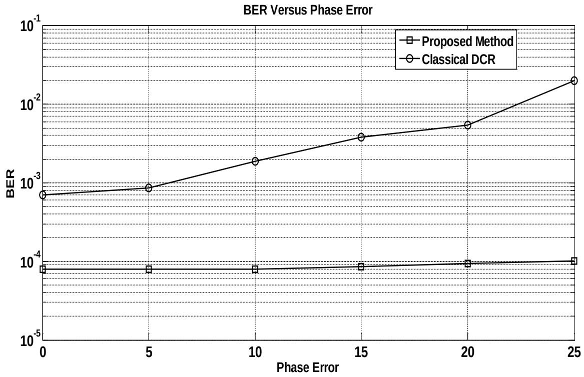

Figure 3: BER versus Phase Error (degree)

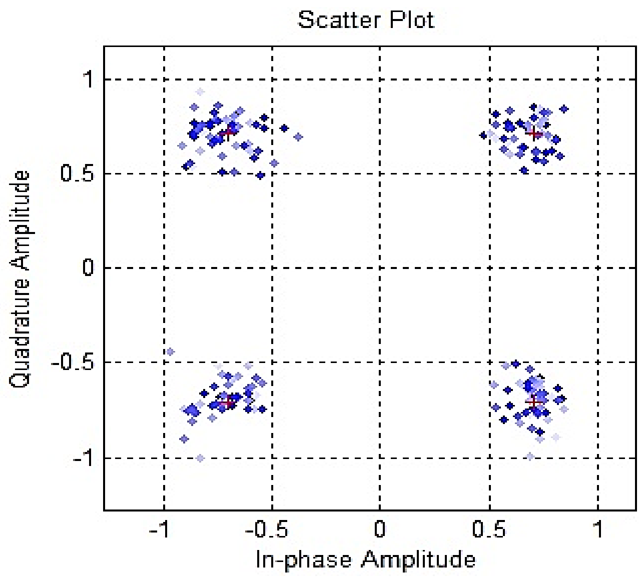

Figure 4: QPSK constellation for classical DCR

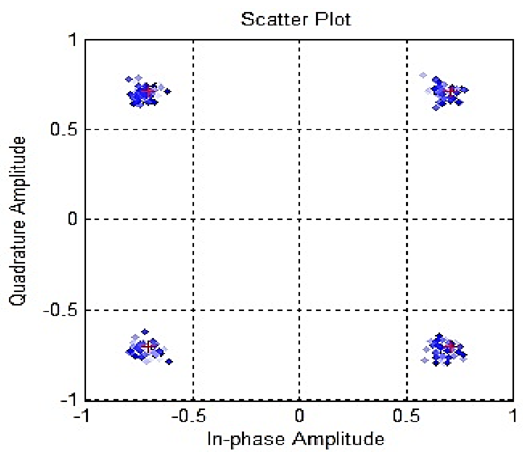

Figure 5: QPSK constellation for Proposed Method

The signal generator generates the local oscillator signal at 2.4GHz and the LO power is 0 dBm. The vector signal generator generates the QPSK-modulated signal at 2.4GHz and the RF power is tuned as per the requirement. Both the signals are synchronized. One more signal generator is utilized to generate an interfering signal or Additive White Gaussian Noise (AWGN) signal. The desired RF signal and interfering RF signal are added with an in-phase power combiner and applied to the RF input port of Classical Direct Conversion Receiver (DCR). The two down converted low-pass filtered output voltages of DCR are sampled by 16-bit Data Acquisition Module and apply to the algorithm, written in MATLAB, for computation of coefficients α_i , β_i. On the base of the computed value of α_i and β_i demodulation of received sampled signal is done and then the received bits are compared with transmitted bits for computation of BER. A large number of data sequences are demodulated to estimate BER. The measured results are presented in Figure 7 and 8.

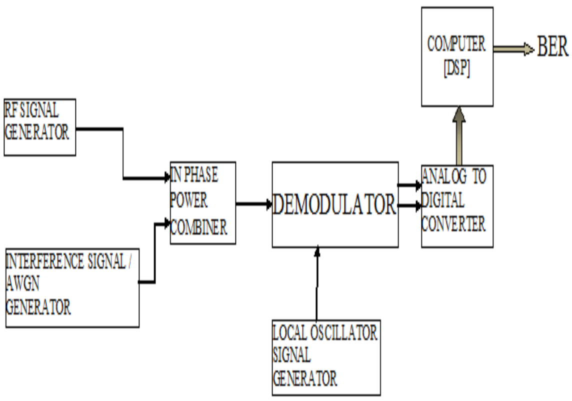

Figure 6: Test-bench utilized for experimental measurement of BER

Figure 7 presents the comparison of the performance of classical DCR with our proposed method in static condition with AWGN. Here comparison has been done with the theoretical BER for QPSK system with simulated and measured BER of classical DCR architecture and proposed method. At BER = 10^{-3}, the implementation loss for proposed DCR architecture is equal to 0.8dB, while for classical DCR it is approximately 2dB.

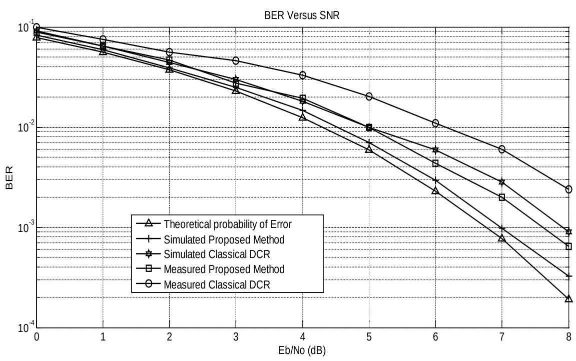

Figure 7: BER versus SNR

Figure 8 presents the sensitivity measurement of the receiver. Sensitivity is the minimum RF input power required to ensure required BER. If required BER is assumed to 10-3, then the measured sensitivity of proposed method is -62.5 dBm, while that of classical DCR is -60.8 dBm.

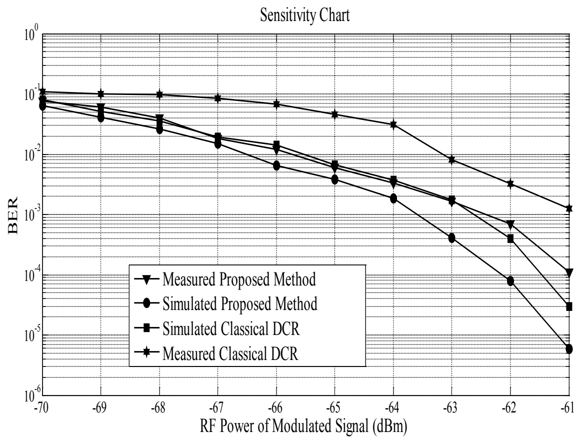

Figure 8: BER versus RF power of signal

5. Conclusions

In this paper a novel method is presented to remove I/Q mismatch distortion. Here proposed method is presented with its principle of operation and self-calibration technique. Self calibration technique adapts calibration constants during the life of the system, rejects the distortion and regenerate the I/Q signals with minimum number of error. Proposed method with self calibration does not required high computational complexity and can be easily implemented in DSP back-end section. This results in to a cost effective upgrading solution. This feature makes the proposed method very attractive.

Experiments are performed on the proposed DCR with QPSK signal to validate the presented theory. Measured results are supporting our claims. With reference to theoretical BER, proposed method with self calibration is implemented with the implementation loss of 0.8dB. The sensitivity achieved with proposed method is -62.5 dBm at BER = 10-3. The sensitivity of the proposed method can be improved with help of LNA, which is not utilized in the proposed test bench. As proposed method is very effective in I/Q mismatch removal, a DCR with this robust, no extra hardware, distortion removal ability will be a good contender for Cognitive Radio Receiver. Here proposed method is tested for only QPSK modulation scheme, but in later it can be tested for other complex modulation scheme, as well proposed method can be expanded to deal with other distortions present in the direct conversion receiver.

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